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To: Marc Pitchford, Bill Malm, Bret Schichtel, Linsey DeBell
From: Nicole Hyslop
Date: March 23, 2005
Subject: Flow Rate Validation

This letter describes our plans to revise and standardize the flowrate validation criteria. This change to our validation criteria will be the first of several changes to standardize and objectify the validation process as described in Warren White's memo circulated on August 30, 2004. This plan is also consistent with our overall plan to focus more of the validation efforts on the raw data instead of the agglomerated concentration data. The new criteria are based on calculation limitations, performance testing, and cutpoint accuracy considerations. These standardized criteria will allow us to track our flow performance over time and look for possible problems associated with operating changes, such as filter lot, filter manufacturer, or filter cassette type. The new flowrate criteria are based purely on technical considerations, and the data usage guidelines for the Regional Haze Rule (RHR) may need to be reviewed in light of this plan. Options for the timing of the implementation of this plan are covered at the end of this memo. I request your feedback on our approach and schedule for implementing these revisions, particularly in light of the RHR requirements.

Currently, the quality control of flowrate data is inconsistent. There is no standard routine for inspecting the continuous flowrate data or set criteria for flagging deviant flowrate data. The procedure is subjective, and thus varies with the person inspecting the data. Also, in the past, the continuous flowrate data were only inspected if the 24-hr average flowrate was well outside the nominal flowrate. The new criteria will be implemented using computer-automated screening of the continuous flowrate data. The flowrate data are obtained from the sites every three weeks, and the data will be screened as soon as a seasonal quarter of data is received, which is several months before the analytical data are available. This early processing of the flowrate data should expedite identification and correction of problems in the field. It should also expedite our final validation process and help us achieve our delivery deadlines.

Following is an overview of flowrate and its relationship to cutpoint for the IMPROVE sampler. The IMPROVE sampler uses passive flow control. **Figure 1** shows a flow diagram for the IMPROVE $PM_{2.5}$ module. The flowrate is controlled by a critical orifice located downstream of the sample filter. A critical orifice is insensitive to downstream pressure changes but sensitive to upstream pressure changes. As the filter loading increases, the pressure drop across the filter increases, lowering the pressure upstream of the critical orifice, and thereby reducing the flowrate. Typically, the decrease in flowrate is around 5% over a 24-hr period (although masked filter cassettes have significant decreases in flowrate even at moderate loadings). These changes in flowrate result in changes in particle-size cutpoint of the cyclone, as described below. Depending on the particle size distribution, the amount of particulate matter collected can change as a result of the shift in cyclone cutpoint.

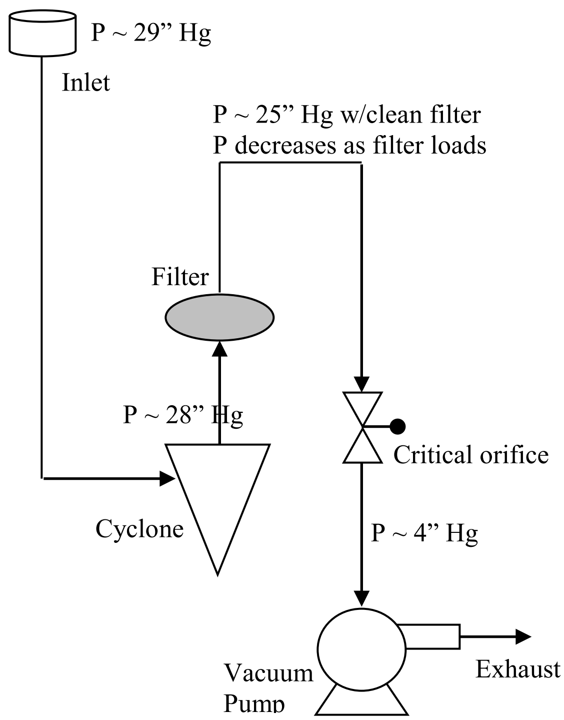


Figure 1. Flow diagram for the IMPROVE $PM_{2.5}$ module.

Flowrate is inversely related to cutpoint as shown in **Figure 2** and modeled in Equation 1:

$$d_{50} = 2.5 - 0.334 * (Q - 22.75) \qquad (1)$$

where Q = flow rate (L/min) and

d_{50} = aerodynamic diameter at which 50% of the particles are collected (μm).

Equation 1 was developed based on flowrates between 18 and 24 L/min. Beyond these flowrates, Equation 1 may not be valid. **Figure 3A** shows the 15-min flowrates over six sampling days for collocated masked and unmasked A-type module filter cassettes at the Mesa Verde site. (The supporting screen of the masked cassette is more restrictive than that of the unmasked cassette. The filters in both cassettes were masked with a paper mask.) **Figure 3B** shows the corresponding 15-min cutpoints over the same six sampling days. The mass loadings were relatively small, 2-3 μg/m^3, on all these days. The decreases in flowrate ranged from 7 to 15% for the masked cassette, while the decreases in flowrate were always less than 4% for the unmasked cassette. Note that all these samples would be considered normal (NM) with respect to flowrate; none of these samples, masked or unmasked, would receive a flow-related validation flag under either the current or the proposed criteria. The validation flags are reserved for more severe clogging events.

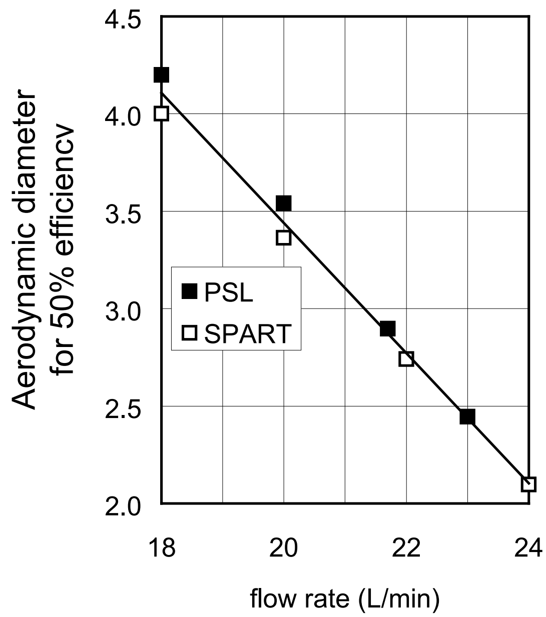
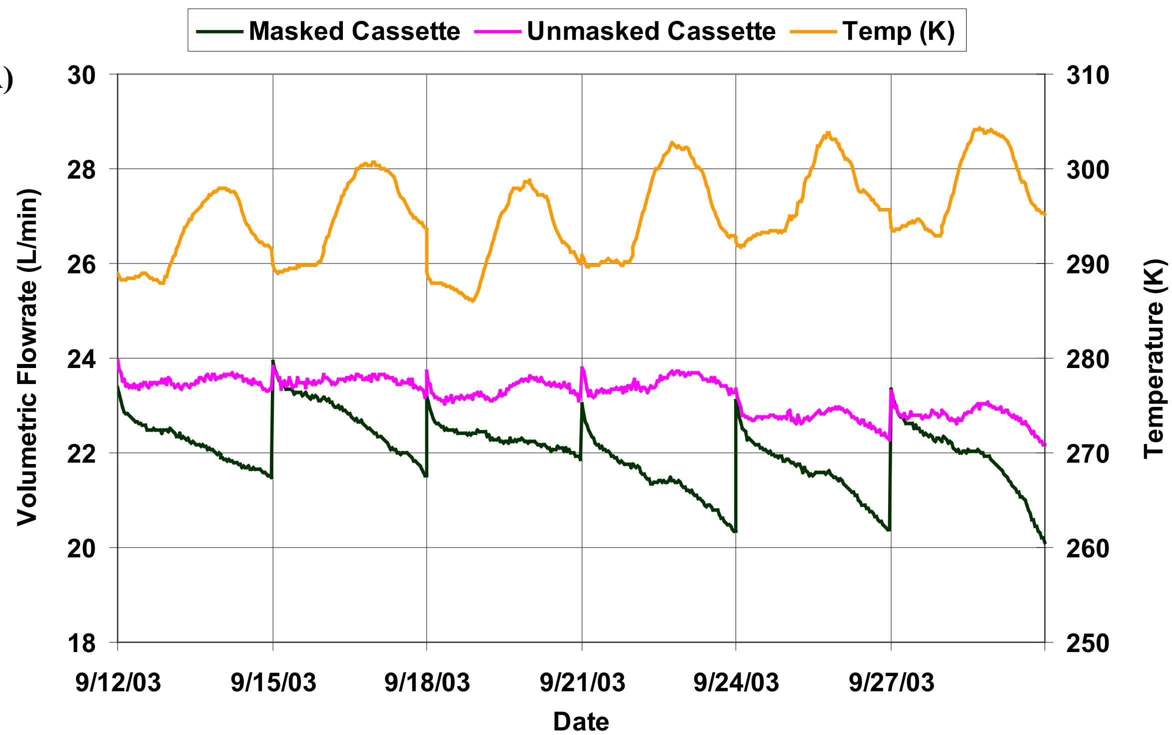


Figure 2. Cyclone cutpoint as a function of flowrate. PSL and SPART represent two different techniques used to generate particles. (Version II Sampler SOP, Appendix I, http://vista.cira.colostate.edu/improve/Publications/SOPs/ucdavis_sops/ti201a_v2.pdf)

A)



B)

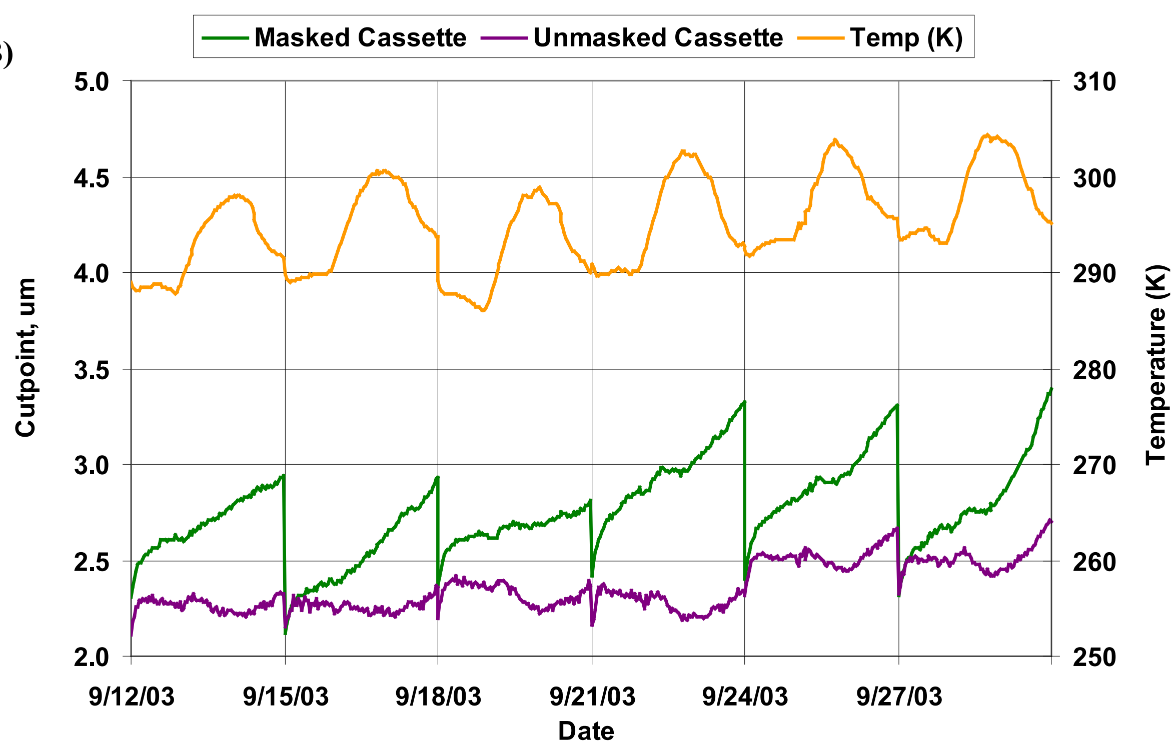


Figure 3. Flowrate (A) and cutpoint (B) values at 15-min resolution for six sampling days at Mesa Verde. The $PM_{2.5}$ concentrations were between 2 and 3 $\mu g/m^3$ on these days. Both cassettes had paper masks under the filters.

The flowrate deviates from the nominal value for different reasons. The first and most common type of deviation, discussed above, is related to particle loading. This type of deviation is characterized by decreasing flowrates over the sampling period. The second type of deviation can result from a variety of problems, such as dirt buildup in the flow path, electronic drift in the pressure transducer outputs (which are used to measure flowrate), varying filter pressure drop, or a failing vacuum pump. This type of deviation is characterized by consistently low (or high) flowrates throughout an individual sampling period. **Figure 4** shows the flowrate at Swanquarter for a single 24-hr sampling period. The flowrate was consistently higher than the nominal flowrate (23.8 L/min) throughout the sampling period. Lastly, these two types of flow deviation can happen simultaneously. **Figure 5** shows the flowrate at Dome Lands for a single 24-hr sampling period. Initially, the flowrate is higher than the nominal flowrate but decreases significantly as the filter loads. Different flow validation criteria are proposed to identify these different problems.

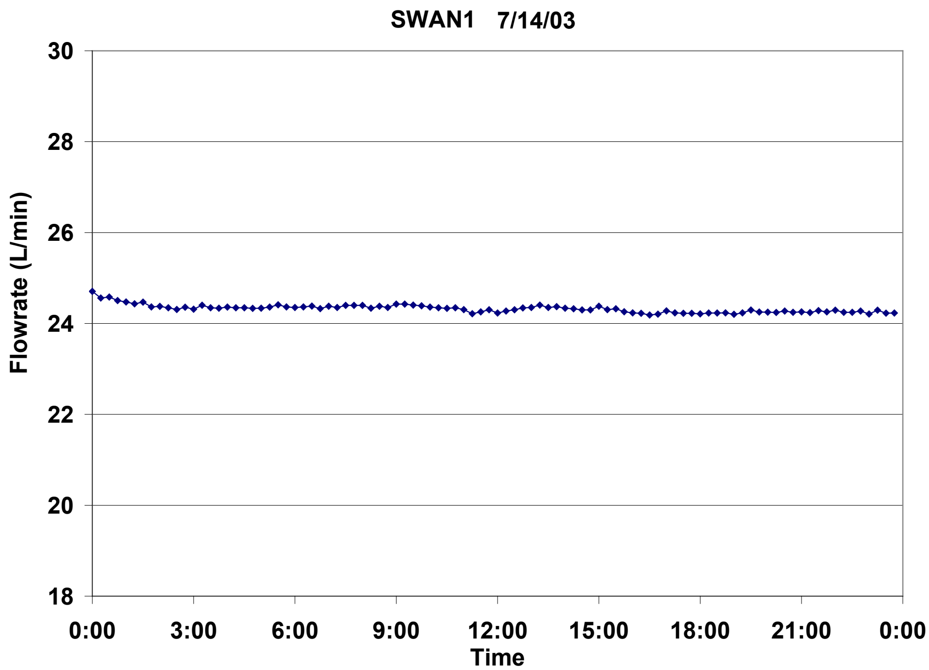


Figure 4. Module A flowrate on July 14, 2003, at Swanquarter. The flowrate is higher than the nominal value (22.8 L/min) throughout the sampling period.

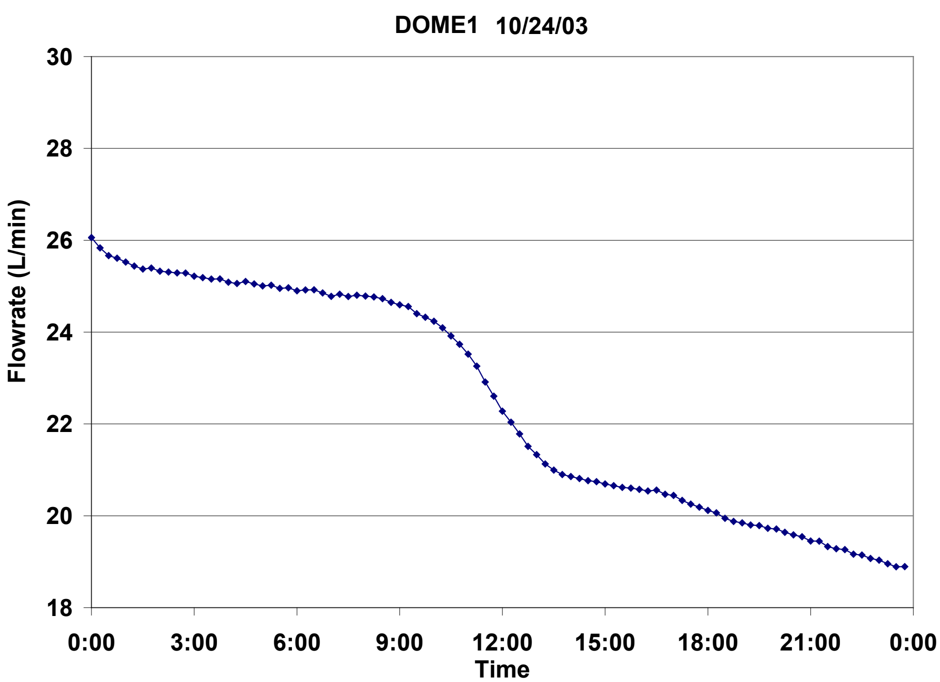


Figure 5. Module A flowrate on October 24, 2003, at Dome Land. The flowrate is initially higher than the nominal value (22.8 L/min) but decreases as the filter loads.

The new validation procedure will retain the four existing flow-related flags, listed in **Table 1**, but will apply them according to new criteria. Currently, the application of validation flags related to flowrate is somewhat subjective, particularly for the CL and CG flags. The current criteria listed for the CG and CL flags have not been applied consistently. In contrast, the new criteria will be applied almost exclusively using computer-automated screening. In addition, the screening would be applied as the flowrate data are received, which is several months prior to the receipt of analytical data. This automated and early screening will expedite our validation process.

Table 1. Flowrate-related validation flag definitions and application criteria.

Validation Flag	Definition	Concentration Reported?	Current Criteria	New Criteria
CL	Clogged Filter	No	Meets the criteria for CG and SO_4 and S values don't agree well	Flowrate less than 15 L/min for more than 1 hour
CG	Clogging Filter	Yes	Final pressure transducer measurement < ½ initial pressure transducer measurement	Flowrate less than 18 L/min for more than 1 hour [1]
LF	Low/high flowrate	Yes	24-hr average flowrate more than 10% above or below nominal flowrate (< 20.5 L/min or > 25.1 L/min)	Average flowrate results in cutpoint outside 2-3 µm (corresponds to flowrates < 21.3 L/min or > 24.3 L/min).
RF	Really low/high flowrate	Yes	24-hr average flowrate more than 17% above or below nominal flowrate (< 19 L/min or > 27 L/min)	Flow greater than 27 L/min for more than 1 hour [2]

1 A small number of samples (5-15) in each quarter passes this criterion but will be classified as a clog (see Figure 5). These samples will be inspected individually and criterion will be developed in the next few months based on the inspections.

2 Samples that were previously flagged as RF for low flowrates will now fall under the CG or CL classifications. Samples that were previously flagged as RF for high flowrates will still be labeled as RF but with an added warning that the cutpoint is not accurately known and is below 1 µm for more than 1 hour.

The new criteria are based on calculation limitations, performance testing, and cutpoint requirements. The criterion for applying a CL flag, flowrate less than 15 L/min for more than 1 hour, is based on the fact that the flowrate equation is inaccurate below approximately 15 L/min. Figure 6 shows a typical (the relationships vary slightly over time and module) relationship between flowrate and pressure transducer measurements. The blue dashed line shows the IMPROVE-calculated flowrate, and the green line shows the actual flowrate. This figure illustrates that below approximately 15 L/min, the IMPROVE-calculated flowrate is not accurate. Only four 15-min flowrates below 15 L/min will be allowed before the air quality data are invalidated (replaced with -999) and flagged as CL.

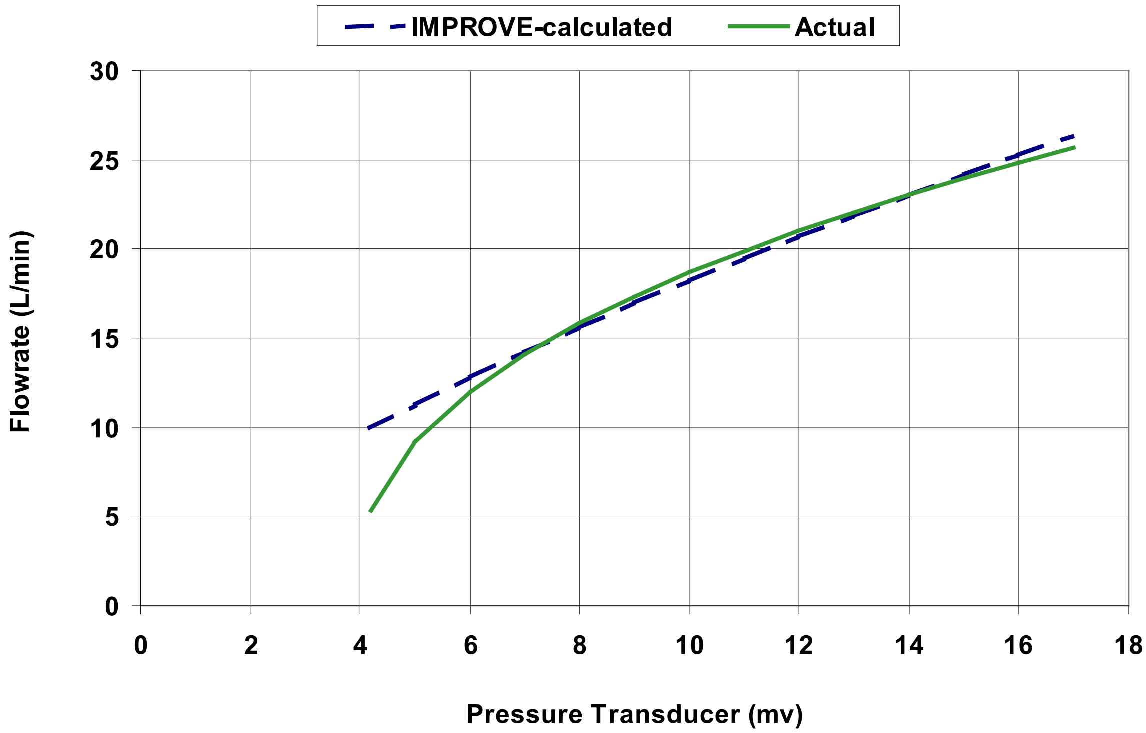


Figure 6. Flowrate versus the pressure transducer reading for the IMPROVE-calculate flowrate and the actual flowrate.

The new criterion for applying a CG flag, flowrate less than 18 L/min for more than 1 hour, is based on cutpoint characterization of the cyclone. As shown in Figure 2, the cyclone cutpoint was only tested between flowrates of 18 and 24 L/min. Therefore, when the flowrate falls below 18 L/min, the cutpoint is undocumented. Only four 15-min flowrates below 18 L/min will be allowed before the sample is flagged as CG.

The new criterion for applying the LF flag, 24-hr average flowrate results in cutpoint outside 2-3 μm range, is based on a reasonable range of particle cutpoints for a data value to be labeled as $PM_{2.5}$. This criterion is stricter than the current LF criterion – flowrate greater than 10% above or below the nominal flowrate.

The new criterion for applying the RF flag, flowrate greater than 27 L/min for more than 1 hour, is based on the cutpoint of the cyclone. Samples that were previously flagged as RF for low flowrates will now fall under the CG or CL classifications. Samples that were previously flagged as RF for high flowrates will still be labeled as RF but with an added warning that the cutpoint is not accurately known and is below 1 μm for more than 1 hour. As shown in Figure 2, the cyclone cutpoint was not characterized above 24 L/min, which is only 5% above the nominal flowrate.

Figure 7 shows the percent of total collected A Module samples that would receive each type of flag under the new validation criteria compared to the percent that received each type of flag under the current (old) validation criteria. Note that the new criteria have only been applied to samples with continuous flowrate data (approximately 90% of the samples), and the old criteria were applied to all the samples. Therefore, the new criteria may result in slightly more LF flags than reflected in this figure. Several patterns are evident in this figure. First, the percent of samples failing one of the flow validation criteria increases in the summer months. This is expected because $PM_{2.5}$ concentrations are higher during the summer months at most sites, and clogging tends to increase with particle loading. Second, the percent of samples failing the CL or CG criteria is decreasing; this trend is due to the replacement of masked filter cassettes with unmasked cassettes at many sites over the last year. Based on these calendar quarters and the proposed validation criteria, the masked filter cassettes are 22 times more susceptible to clogging (CL or CG) than the unmasked filter cassettes. We are planning to remove more of the masked cassettes in the coming year, and the number of CL and CG flags should continue to decrease as the masked cassettes are removed from the network. **Table 2** lists the number of samples that correspond to the percent values shown in Figure 7. Note that Figure 7 and Table 2 summarize the flagging for the A Module filters only. The same criteria will be applied to the B and C Modules. The percent of B or C Module samples flagged will typically be lower than for the A Module because these modules are not as susceptible to clogging.

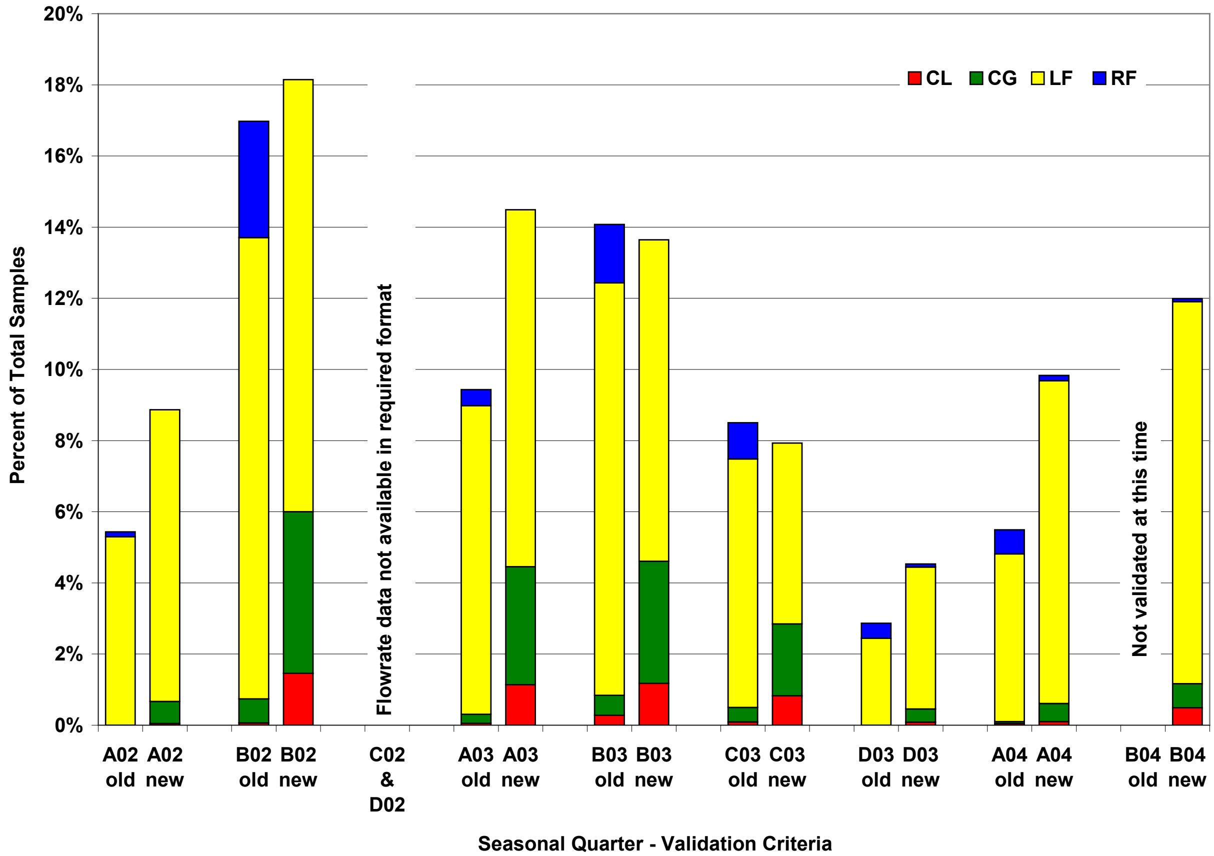


Figure 7. Percent of samples with flow-related validation flags using the current (old) and proposed (new) criteria for each calendar quarter in the last three years. Seasonal quarter A includes March, April, and May; B includes June, July, and August; C includes September, October, and November; and D includes December, January, and February.

Table 2. Number of samples with flow-related validation flags using the current (old) and new criteria for each calendar quarter in the last three years.

Flag	A02 - old	A02 - new	B02 - old	B02 - new	A03 - old	A03 - new	B03 - old	B03 - new
CL	0	2	3	71	3	63	15	63
CG	0	27	33	221	14	184	30	184
LF	230	356	631	591	481	556	621	484
RF	6	0	159	0	25	0	88	0

Flag	C03-old	C03 - new	D03 - old	D03 - new	A04-old	A04 - new	B04 - old	B04 - new
CL	5	46	0	5	3	6	Not Validated Yet	29
CG	23	113	0	21	3	31		40
LF	390	284	139	227	287	552		636
RF	57	0	24	5	41	9		5

It is obvious that this plan will make a noticeable difference in the validation flag distribution in the IMPROVE dataset. Three possible approaches to implementing this plan are described below.

1) **Look forward:** Apply new criteria as soon as possible to new data and do not apply the criteria to data that have already been submitted at this time. Under this scenario, the criteria would likely be applied starting with August or September 2004 data. This change to our validation criteria will be the first of several changes to standardize and objectify the validation process. Therefore, it may be most efficient to delay a decision on whether to reprocess the old data until the entire validation process has been reviewed and revised.

2) **Look forward and backward:** Apply new criteria as soon as possible to both old and new data. These criteria could be applied back to the installation of the Version II sampler at each site, which is mid-2000 in most cases. The work effort required by this option is significant given our current data management situation. We would need to work out the details of this option with CIRA.

3) **Wait:** Do not apply the new flowrate criteria until the entire validation process has been reviewed and revised and the new UC-Davis data management system is available. These processes will take approximately two years to complete.

Please provide feedback on the approach and schedule for this plan to me by Friday, April 1, 2005.

Addendum to Memo from Nicole Hyslop, Dated: 23 March 2005, Subject: Flow rate validation
13 December 2006

During summer 2006, Jay Turner characterized the IMPROVE cyclone and found that the equations relating cutpoint to flowrate developed at UCD are invalid (Figure 2 and Equation 1 in the original memo). Therefore, the validation flags based on flowrate must be revised. Dr. Turner's characterization work was consistent with the characterization performed by John and Reischl (1980), and we have therefore decided to use the original John and Reischl (1980) equations for the IMPROVE cyclones. Figure 1A shows the two equations and a few of the data points collected in Dr. Turner's study. There are two important features to note in Figure 1A: 1) the John and Reischl (1980) equation is much less sensitive to flow rate than the equation we have used in the past, and 2) at the IMPROVE nominal flowrate of 22.8 LPM, the cutpoint is 2.4 μm, not 2.5 μm.

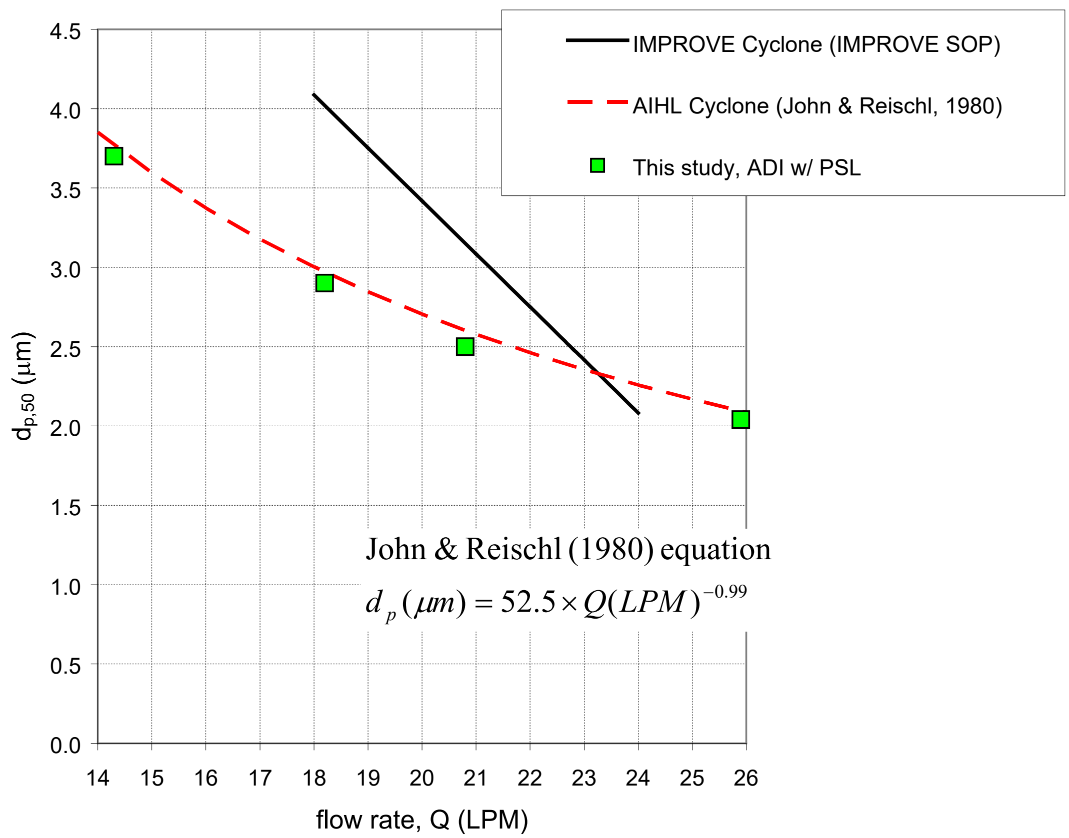


Figure 1A. Diameter at which 50% of the particles are collected by the cyclone ($d_{p,50}$, also known as cutpoint) as a function of flow rate.

We have decided to maintain the existing criteria for the CL, CG, and RF flags. Table 1A lists the criteria and their meanings based on the John and Reischl (1980) equation. The CL flag is based on the accuracy of the flowrate equation and is therefore not affected by this new information. The CG and RF flag criteria are now stricter in terms of cutpoint because the equation is less sensitive to cutpoint. We have decided to change the criterion for the LF flag because the prior criterion is not centered on 2.5 um as a result of the shift in the equation. The updated criteria will be applied to data starting in January 2005. Figure 2A shows the average flow rate distribution for 2003 along with the current and updated criteria for the LF flag. The number of samples with LF flags in the A, B, and C modules are listed in the bars illustrating the range of the criteria.

Table 1A. Updated flowrate-related validation flag definitions and application criteria.

Validation Flag	Definition	Concentration Reported?	March 23, 2005, Criteria	Updated criteria based on John & Reischl equation
CL	Clogged Filter	No	Flowrate less than 15 L/min for more than 1 hour	Same criterion - based on the flow rate calculation inaccuracy not cutpoint
CG	Clogging Filter	Yes	Flowrate less than 18 L/min for more than 1 hour	Same criterion, corresponds to a cutpoint of 3 μm
LF	Low/high flowrate	Yes	Average flowrate results in cutpoint outside 2 to 3 μm (corresponds to flowrates of 21.3 L/min and 24.3 L/min).	Average flowrate results in cutpoint outside 2.25 to 2.75 μm (corresponds to flowrates of 19.7 and 24.1 L/min)
RF	Really high flowrate	Yes	Average flow rate greater than 27 L/min	Same criterion, corresponds to a cutpoint of 2 μm

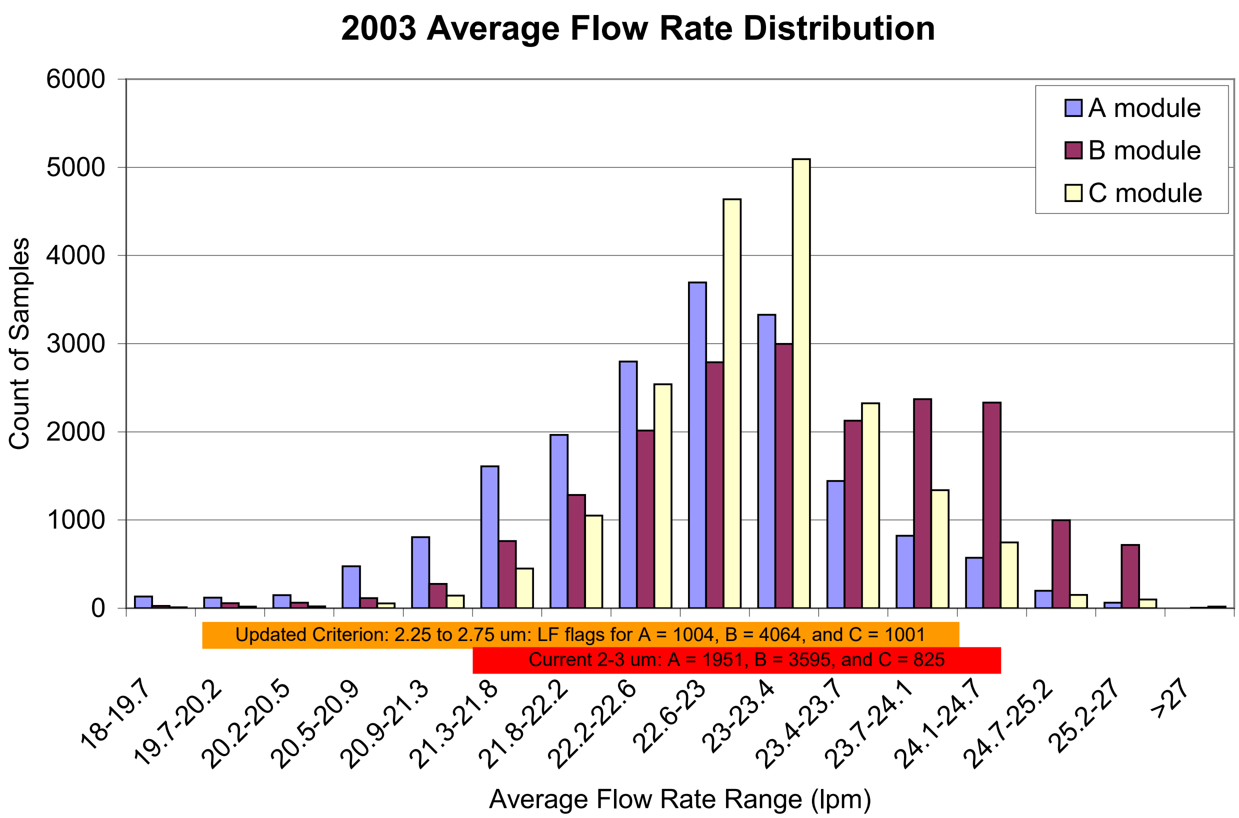


Figure 2A. Average flow rate distribution in 2003. The two bars below the graph show the acceptable ranges of flowrates for the updated LF criterion, based on the John and Reischl equation, and the LF criterion described in the March 2005 memo, which used the UCD equation. The previous criterion corresponded to cutpoint range of 2 to 3 μm under the UCD equation but corresponds to a range of only 2.23 to 2.54 μm with the John and Reischl equation.